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The Vehicle Dynamic Parameters Recognition of In-wheel Motor Driven Electric Vehicle

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Abstract

The yaw rate, sideslip angle, and velocity of the vehicle is an important part of the vehicle dynamic control system .The measurement of vehicle dynamic parameters are costly and usually with great errors. A method is proposed in terms of the recognition of vehicle dynamic parameters based on the corning kinetics and corning geometry of the vehicle. The yaw rate and sideslip angle is estimated by using of velocity of wheels. The method is derived from the vehicle geometric kinetics and is different from the tradition method of using velocity differences between every wheel to express the yaw rate. Vehicle sideslip is taken into account, indicating that the effect of tire sideslip on vehicle kinetics is considered, thus make it more accurate in estimating the kinematic parameters. The estimation method is validated by simulation based on the vehicle nonlinearity model.

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1. Overview of the Corning Kinematic Parameters Recognition

At present, the direct measurement of vehicle slip angle is costly, and can not be accepted on industrial products. Hence, in vehicle dynamic controls, the slip angle is seldom achieved by the direct measurement or even not used as the controlling variable in the system. Besides that, the yaw rate sensor, compared with other common sensors is expensive.

Based on the aforementioned reasons, only a few vehicles are launched with the active vehicle dynamic control system. To benefit more customers with this advanced system, appropriate cutting of the system cost is a possible solution. One feasible method is to estimate the required parameters with the data from the limited number of sensors that are acceptable on price, such as the sensor of angular velocity of wheels and the sensor of vehicle acceleration.

Many researchers used the angular velocity of wheels, longitude and lateral acceleration to estimate vehicle kinematic parameters. Paul *et al.* [1] proposed the recognition of slide angle using yaw rate and

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steering torque for steer-by-wire vehicles. Behzad *et al.* [2][6] employed Kalman filter to estimate the kinematic parameters through angular and linear velocity of wheels as well as the tire characteristics. Aleksander *et al.* [3] applied the method to achieve the yaw rate and slide angle from wheel speed and lateral acceleration. Hideaki Sasaki *et al.* [4] implemented the neural network to recognize the slide angle according to the yaw rate and lateral acceleration. Jihan Ryu [5] performed the estimation of vehicle roll angel and road gradient, while Ali Y. Ungorn [7] proposed recognition of the lateral speed.

2. Kinematic Parameter Recognition of In-wheel Motor Driven Vehicles

The measurement of vehicle kinematic parameters are costly and usually with great errors. However, it is much easier and cheaper to get the angular velocity with more accuracy and quick response on in-wheel motor driven vehicle. The linear velocity on wheel center is an important part of the vehicle dynamic parameters. The cost of measurement on controlling parameter will be greatly decreased if the yaw rate, sideslip angle and vehicle velocity et al. can be estimated by the four linear velocities on wheel center. In this paper, a method is proposed in terms of the recognition of vehicle kinematic parameters based on the corning kinetics and corning geometry of the vehicle.

In a vehicle with independent front and rear wheel steering, assume each wheel has a velocity sensor to get its center velocity. Make $v_{fl}, v_{fr}, v_{bl}, v_{br}$ to be center velocity of front-left wheel, front-right wheel, rear-left wheel and rear-right wheel respectively. A simple estimation of vehicle velocity and yaw rate is:

$$v = \frac{1}{4}\left(v_{fr} + v_{br} + v_{fl} + v_{bl}\right) \tag{1}$$

$$r = \frac{1}{2B}\left(v_{fr} + v_{br} - v_{fl} - v_{bl}\right) \tag{2}$$

Where B is the tread of wheels

This method has some validity when the vehicle is at low speed. However, the steering angles of front wheels are different with those of rear wheels. On most of the vehicles, rear wheels even don't steer. This means all the four wheels on the vehicle have different linear velocity, thus make it hard to know for which point of the vehicle body you are calculating the velocity and yaw rate.

If the sideslip angle is not considered, the vehicle kinetic status can be expressed as

$$\left.\begin{array}{l} \dot{x} = v\cos\psi \\ \dot{y} = v\sin\psi \\ \dot{\psi} = Kv \end{array}\right\} \tag{3}$$

Where $[x, y, \psi]^T$ stands for the position and direction vector of vehicle; x, y are the coordinates of vehicle position; ψ is the direction or the yaw angle (angle between X axle and longitude symmetrical line); K is the curvature of vehicle track; v is the vehicle speed. Usually, vehicle position is determined by the center of mass, as is shown by C in Figure1. Unless the steer angles of front wheel and rear wheel are in the same value but opposite direction, when the vehicle is steering around point P, PC line is not perpendicular with the vehicle longitude symmetric line, which means the velocity at C is not satisfied in Equation(3). This is because in Equation(3), sideslip angle is not considered. So, here Equation(3) is modified to take the sideslip angle into account:

$$\left.\begin{array}{l} \dot{x} = v\cos(\psi + \beta) \\ \dot{y} = v\sin(\psi + \beta) \\ \dot{\psi} = Kv \end{array}\right\} \tag{4}$$

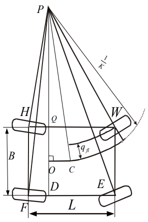

Figure 1 Geometric relationship between vehicle kinetic parameters

All the vectors are in terms of point C; $\beta = \angle CPO$ is the vehicle sideslip angle; v is the velocity at point C; K is the curvature of vehicle track at point C. The new non-holonomic constraint equation is:

$$-\dot{x}\sin(\psi+\beta)+\dot{y}\cos(\psi+\beta)=0 \tag{5}$$

Assume each wheel satisfies the non-holonomic constraint equation (5). The direction of velocity on wheel center is perpendicular with the connection line between P and the wheel center. According to the relationship of vehicle center velocity and wheel center velocity, Equation(5) can be solved

$$\left(\frac{\sin\beta}{K}+L_f\right)^2+\left(\frac{\cos\beta}{K}-\frac{B}{2}\right)^2=\left(\frac{1}{K}-q_{fl}\right)^2 \tag{6}$$

Multiply Equation(5-6) by K^2, yielding:

$$\frac{1}{4}\left(4L_f^{\ 2}+B^2\right)K^2+1-KB\cos\beta+2KL_f\sin\beta=\left(1-q_{fl}K\right)^2 \tag{7}$$

Use ΔPQH ΔPDF ΔPDE, yielding:

$$\frac{1}{4}\left(4L_r^{\ 2}+B^2\right)K^2+1-KB\cos\beta-2KL_r\sin\beta=\left(1-q_{bl}K\right)^2 \tag{8}$$

$$\frac{1}{4}\left(4L_r^{\ 2}+B^2\right)K^2+1+KB\cos\beta-2KL_r\sin\beta=\left(1+q_{br}K\right)^2 \tag{9}$$

$$\frac{1}{4}\left(4L_f^{\ 2}+B^2\right)K^2+1+KB\cos\beta+2KL_f\sin\beta=\left(1+q_{fr}K\right)^2 \tag{10}$$

It is easy to say that vehicle center velocity satisfies the Equation(5-11)

$$v=\frac{v_{fl}}{1-q_{fl}K}=\frac{v_{fr}}{1+q_{fr}K}=\frac{v_{bl}}{1-q_{bl}K}=\frac{v_{br}}{1+q_{br}K} \tag{11}$$

Substitute Equation(5-11) into Equation(5-7)~(5-10). The following equations can be derived:

$$v_{fr}^2+v_{fl}^2+v_{br}^2+v_{bl}^2=\left(2L_f^{\ 2}+2L_r^{\ 2}+B^2\right)\dot{\psi}^2+4v^2+2\left(L_f-L_r\right)\dot{\psi}v\sin\beta \tag{12}$$

$$v_{fr}^2+v_{fl}^2-v_{br}^2-v_{bl}^2=\left(2L_f^2-2L_r^2\right)\dot{\psi}^2+4L\dot{\psi}v\sin\beta \tag{13}$$

$$v_{fr}^2-v_{fl}^2+v_{br}^2-v_{bl}^2=4B\dot{\psi}v\cos\beta \tag{14}$$

Obviously, when β =0, the wheel center velocities of front wheel and rear wheel are identical. Because $\dot{\psi}v$ is non-zero(provided that only during the pure slipping $\dot{\psi}$ =0), β can be solved from Equation(5-13) and (5-14).

$$\beta=\tan^{-1}\left(\frac{B}{L}\cdot\frac{v_{fr}^2+v_{fl}^2-v_{br}^2-v_{bl}^2-2\left(L_f^2-L_r^2\right)\dot{\psi}^2}{v_{fr}^2-v_{fl}^2+v_{br}^2-v_{bl}^2}\right) \tag{15}$$

This equation may have some problems with small vehicle track, because tiny differences of wheel velocity should be examined between each wheel. But in vehicle dynamic control, there usually have large velocity difference between each wheel. So, when β is solved, Equation(5-13) and (5-14) yield to :

$$\dot{\psi}^2 v^2 = \frac{1}{16L^2}\left(v_{fr}^2 + v_{fl}^2 - v_{br}^2 - v_{bl}^2 - 2\left(L_f^2 - L_f^2\right)\right)^2 + \frac{1}{16B^2}\left(v_{fr}^2 - v_{fl}^2 + v_{br}^2 - v_{bl}^2\right)^2 \qquad (16)$$

From Equation(5-13)

$$\dot{\psi} v \sin\beta = \frac{v_{fr}^2 + v_{fl}^2 - v_{br}^2 - v_{bl}^2 - \left(2L_f^2 - 2L_r^2\right)\dot{\psi}^2}{4L} \qquad (17)$$

Substitute Equation (5-17) into Equation(5-12), yields to:

$$\left(L^2 + B^2\right)\dot{\psi}^2 + 4V^2 = v_{fr}^2 + v_{fl}^2 + v_{br}^2 + v_{bl}^2 + \frac{2\left(L_f - L_r\right)\left(v_{fr}^2 + v_{fl}^2 - v_{br}^2 - v_{bl}^2\right)}{4L}$$

Simplify the upper equation, yielding:

$$V^2 = \frac{4L\left(v_{fr}^2 + v_{fl}^2 + v_{br}^2 + v_{bl}^2\right) + 2\left(L_f - L_r\right)\left(v_{fr}^2 + v_{fl}^2 - v_{br}^2 - v_{bl}^2\right)}{16L} - \frac{\left(L^2 + B^2\right)}{4}\dot{\psi}^2$$

$$= \Delta + \frac{L^2 + B^2}{4}\dot{\psi}^2 \qquad (18)$$

$$\Delta = \frac{4L\left(v_{fr}^2 + v_{fl}^2 + v_{br}^2 + v_{bl}^2\right) + 2\left(L_f - L_r\right)\left(v_{fr}^2 + v_{fl}^2 - v_{br}^2 - v_{bl}^2\right)}{16L}$$

Substitute into Equation(5-16)

$$\frac{L^2\left(L^2 + B^2\right) + \left(L_f^2 - L_r^2\right)^2}{4L^2}\dot{\theta}^4 + \left(\Delta + \frac{\left(L_f^2 - L_r^2\right)(\Lambda)}{4L^2}\right)\dot{\psi}^2$$

$$-\frac{1}{16L^2}\left(\Lambda - 2\left(L_f^2 - L_f^2\right)\right)^2 - \frac{1}{16T^2}(\Gamma)^2 = 0 \qquad (19)$$

$$\Lambda = v_{fr}^2 + v_{fl}^2 - v_{br}^2 - v_{bl}^2 \qquad \Gamma = v_{fr}^2 - v_{fl}^2 + v_{br}^2 - v_{bl}^2$$

Make

$$F_A = \frac{L^2\left(L^2 + B^2\right) + \left(L_f^2 - L_r^2\right)^2}{4L^2}$$

$$F_B = \frac{4L\left(v_{fr}^2 + v_{fl}^2 + v_{br}^2 + v_{bl}^2\right) + 2\left(L_f - L_r\right)\left(v_{fr}^2 + v_{fl}^2 - v_{br}^2 - v_{bl}^2\right)}{16L} + \frac{\left(L_f^2 - L_r^2\right)\left(v_{fr}^2 + v_{fl}^2 - v_{br}^2 - v_{bl}^2\right)}{4L^2}$$

$$F_C = -\frac{1}{16L^2}\left(v_{fr}^2 + v_{fl}^2 - v_{br}^2 - v_{bl}^2 - 2\left(L_f^2 - L_f^2\right)\right)^2 - \frac{1}{16B^2}\left(v_{fr}^2 - v_{fl}^2 + v_{br}^2 - v_{bl}^2\right)^2$$

Thus

$$r = \dot{\psi} = sign(\delta)\sqrt{\frac{-F_B + \sqrt{F_B{}^2 - 4F_A F_C}}{2F_A}} \qquad (20)$$

Equation(15) and (20) can be used to estimate yaw rate and sideslip angle by using of wheel center velocities. They are derived from the vehicle geometric kinetics and are different from the tradition method of using velocity differences between every wheel to express the yaw rate. In these equations, sideslip is taken into account, indicating that the effect of tire sideslip on vehicle kinetics is considered here, thus make it more accurate in estimating the kinematic parameters.

One thing needs to be pointed out here is that the precondition of estimation the vehicle kinematic parameters is the use of rotating speed of the wheel to express the wheel center speed, in other words the use of precisely determined slipping rate of the wheel. So the accurate estimation is fairly possible in condition that the slipping rate of the wheel is monitored in real time.

3. Simulation validation

Because there are precedents of using wheel rotating speed to estimate the yaw rate, only the recognition of sideslip angle is validated. The practical value of sideslip angle under step input at steering wheel is compared with the theoretical value calculated by the aforementioned equations to validate the accuracy of recognition of sideslip angle using wheel rotating speed.

Figure2 is the sideslip angle under 0.1rad step input of the steering angle at vehicle speed of 80km/h. It can be seen that the recognition value follows the practical value well enough. Under the same road and vehicle speed, 0.15rad step steering angle is inputted at the steering wheel. Figure 3 shows the results of recognized and practical sideslip angle. Practical values are closely followed by the recognized values. However, there are many factors that will affect the vehicle yaw rate and the sideslip angle. Further vehicle ground tests need to be carried out for the validation.

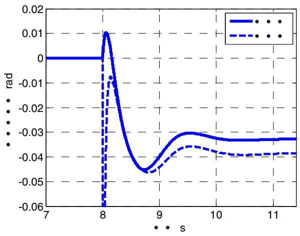

Figure 2 0.1rad step input

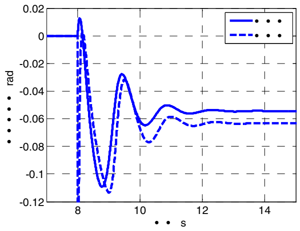

Figure 3 0.15rad step input

4. Conclusion

A method is proposed in terms of the recognition of vehicle dynamic parameters based on the corning kinetics and corning geometry of the vehicle. The yaw rate and sideslip angle is estimated by using of velocity of wheels. The method is derived from the vehicle geometric kinetics and is different from the tradition method of using velocity differences between every wheel to express the yaw rate. Vehicle sideslip is taken into account, indicating that the effect of tire sideslip on vehicle kinetics is considered, thus make it more accurate in estimating the kinematic parameters. The estimation method is validated by simulation based on the vehicle nonlinearity model.

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